Inactivation cross section of yeast cells irradiated by heavy ions*

ZHANG Chunxiang, LUO Daling
(*Zhongshan University, Guangzhou 510275*)

Abstract Inactivation cross sections for haploid yeast cell strain 211a have been calculated as 1-hit detector based on the track theory in an extended target mode and a numerical calculation of radial dose distribution. In the calculations, characteristic dose D_0 is a fitted parameter which is obtained to be 42 Gy, and "radius" of hypothetical target a_0 is chosen to be 0.5μm which is about the size of nucleus of yeast cells for obtaining an overall agreement with experimental cross sections. The results of the calculations are in agreement with the experimental data in high LET (linear energy transfer) including the thindown region.

Keywords Haploid yeast cell, Yeast cell, Radial dose distribution, Inactivation cross section

1 Introduction

The calculations of inactivation cross sections for heavy ions in the track width regime displaying thindown for E. Coli B/r and Bs-1, and for Bacillus Subtilus are straightforward for these 1-hit detectors based on the Katz track theory.[1] Calculations for V-79 hamster cells are more complex. They follow the original development of this model for eucaryotic cells, and make use of the cross sections calculated for hypothetical internal targets which are then asserted to be proportional to the measured cellular inactivation cross sections. In mammalian cells inactivated cross sections are always smaller than the nuclear cross sectional area, which means that cells are not killed by single traversals. It shows that mammalian cells are acted to be multi-hit detector.

The yeast appears to be an especially interesting object, not only because it is radiobiologically well known, but even more because of its physical dimension. The dimensions of bacteria are much smaller and nuclei of mammalian cells considerable larger. Yeast cells may thus be used to probe the effectiveness of different spatial distribution of energy deposition.

The calculations of the inactivation cross section based on the track theory to one hit detector in an extended target mode have been done by authors with different radial dose distribution formula and for different biological samples.[5~7] Due to the lack of systematically measured data either for certain energy range and some types of ions, or no D_{37} for γ-rays in the same experiment, comparisons of these calculations of the cross section with experimental data in wide range of LET, especially in the high LET region for yeast cells have not been reported with satisfaction. In the caluclations the characteristic dose D_0 is equal to 42 Gy which is a value extracted from experimental data as D_{37} gamma dose, and the "radius" of hypothetical target a_0 as a fitted parameter is equal to 0.5μm for ob-

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taining an overall agreement with experimental cross sections. The results of the calculations are in good agreement with experimental data in high LET region.[2]

2 Formulation

In this study the numerical integration method was used to calculate the radial distribution of dose around a heavy ion path proposed by Zhang, *et al.*[7] In the method, a logarithmic polynomial instead of two power functions is used to describe the range-energy relationship of electrons and the angular distribution of ejected secondary electron is taken into account. The results of these calculations of radial distribution of dose around the path of a heavy ions showed in better agreement with experimental data in comparison with the analytic formula used before[8], especially at the maximum radial distance of energy deposition by delta rays. The cut off radial distances of delta ray emitted from the interaction of different incident energies of the particles with the medium are comparable with those given by Kiefer *et al*[9]. This improvement in the calculation of radial distribution of dose is important in the calculation of the thindown problem.

For an electron initially bound to an atom with mean ionization potential I, the secondary electron liberated by a passing ion follows the classical kinematics, and the angular distribution for the secondary electron is expressed by,

$$\cos\theta = \frac{\omega}{\omega_{\mathrm{m}}} \tag{1}$$

The distribution of radial dose around a path of a heavy particle in water is given by:

$$D(t) = \frac{CZ_{\mathrm{eff}}^2\omega_{\mathrm{m}}^{1/2}}{2\pi\beta^2 t}\int_t^T \frac{1}{(\omega_{\mathrm{m}} - g^{-1}(r))^{1/2}}\cdot(g')^{-1}\{r - [\frac{\omega_{\mathrm{m}}}{\omega_{\mathrm{m}} - g^{-1}(r)}]^{1/2}\cdot t\}\cdot\frac{g^{-1}(r)}{(g^{-1}(r)+I)^2}\cdot\mathrm{d}r \tag{2}$$

where ω is the energy of electron ejected at an angle to the ion path, ω_{m} is the maximum energy delivered to a secondary electron of mass m by an ion moving at relative speed $\beta = v/c$ (c is the speed of light). If r is the range of secondary electron with the initial energy, the range-energy relationship of the secondary electron is expressed by

$$r = g(\omega) \tag{3}$$

and

$$\omega = g^{-1}(r) \tag{4}$$

the maximum range of the secondary electron with energy ω_{m} is

$$T = g(\omega_m) \tag{5}$$

and Z_{eff}^2 is the effective charge of incident particle.

Fig.1 shows that the radial dose distributions of 1 MeV proton measured (symbols) and calculated (curve) by Krämer and Kraft[10] based on the binary encounter approximation (dot line) are compared with that calculated in this work (solid line). Fig.2 shows that the radial dose distributions of 41.1 MeV oxygen ions measured (symbols) and calculated (curve) by Krämer and Kraft[10] based on the binary encounter approximation (dot line) are compared with that by this work (solid line).

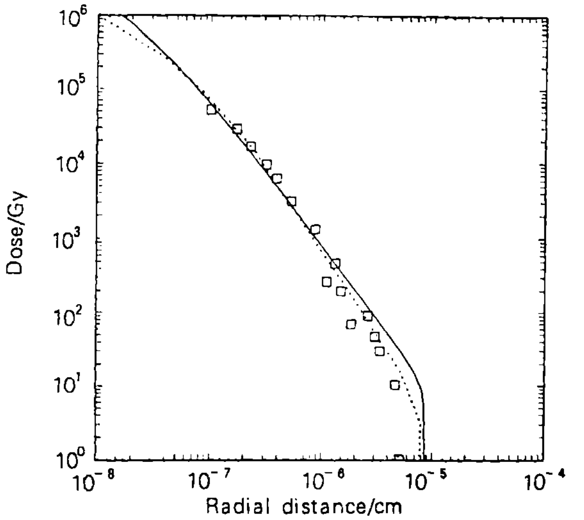

Fig.1 Comparison of the radial dose distribution of 1 MeV proton measured (symbols) with the calculated curve by Krämer and Kraft[10] based on the binary encounter approximation (dot line) and that by this work (solid line)

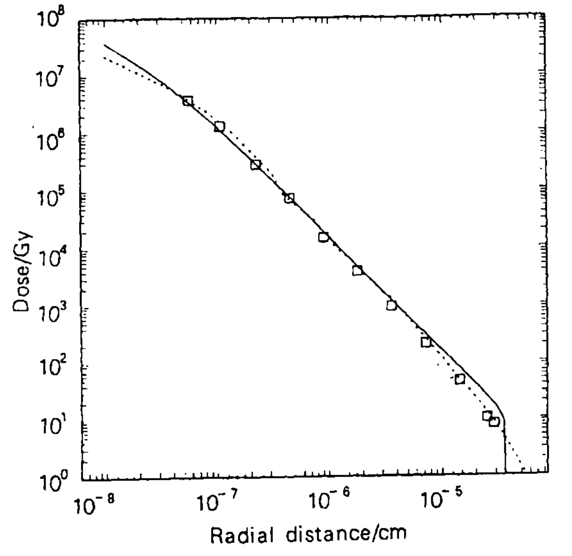

Fig.2 Comparison of the radial dose distribution of 41.1 MeV oxygen ions measured (symbols) with the calculated curve by Krämer and Kraft[10] based on the binary encounter approximation (dot line) and that by this work (solid line)

The inactivation cross sections calculated for a hypothetical target of "radius" a_0 and for one hit detector is expressed as,

$$\sigma = 2\pi \int_0^T (1 - e^{-\overline{D}(t)/D_0}) t \mathrm{d}t \qquad (6)$$

Where $\overline{D}(t)$ is the average dose at the target which is a short cylinder of radius a_0 at a distance from the ion path. D_0 is the characteristic dose. Since the theory is straight forward in conceptual aspect, the test of this theory depends on how well the experimental data are measured in systematic way, and how accurate the radial distribution of dose represents the physical reality.

3 Results and discussion

Based on the experimental D_{37} for gamma rays[2], D_0 is equal to 42 Gy in the calculation and taking account of the target radius a_0 of yeast cells as a fitted parameter in the calculation. It was obtained that a_0 is adjusted to 0.5 μm for a good fit to the

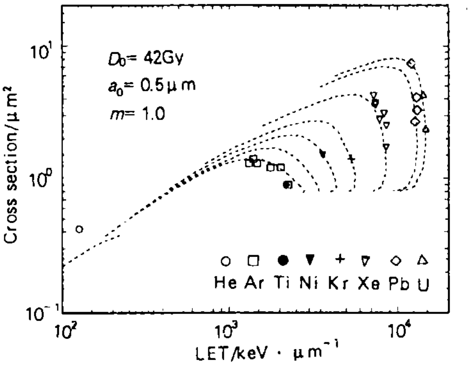

Fig.3 Comparison of the inactivation cross sections of dried yeast cells by accelerated heavy ion of very high LET measured by Kiefer[2] (symbols in triangle, diamond, circle, square and cross) with the model calculation based Katz track theory[2] and the radial dose distribution calculation (dashed line) by Zhang *et al*[7]

experimental inactivation cross sections as whole. Besides, there is no free adjusted parameters in the calculation. A comparison of the measured inactivation cross sections of hapoid yeast cells by accelerated heavy ion of very high LET with the calculations was showed in Table 1. The experimental data were plotted as symbols while the calculation was plotted as curve in Fig.3.

Table 1 Comparison of the measured inactivation cross sections[2] of haploid yeast cells stain 211a by accelerated heavy ion of very high LET with the model calculation based on the track theory[1] and the radial dose distribution calculation[7]

Ion	Specific energy /MeV·u^{-1}	LET /×10^{3}keV·μm^{-1}	Cross section /μm^2 (Exp.)[2]	Cross section /μm^2 (Theory)
He	0.65	0.13	0.42	0.26
Ar	9.3	1.31	1.3	1.4
	8.4	1.39	1.4	1.4
	7.6	1.47	1.3	1.4
	5.3	1.76	1.2	1.3
	3.8	2.03	1.2	1.2
	2.8	2.24	0.9	1.1
Ti	6.6	2.18	0.9	1.6
In	4.4	3.60	1.5	1.6
Kr	3.2	5.33	1.4	1.4
Xe	8.0	7.23	4.2	3.5
	7.3	7.40	3.7	3.3
	5.7	7.83	2.8	2.7
	3.9	8.32	3.1	1.9
	2.8	8.55	1.7	1.5
	2.2	8.59	2.5	1.2
Pb	7.7	12.12	7.4	4.5
	3.5	13.10	3.3	2.0
	2.3	13.00	4.1	1.4
	1.7	12.70	2.7	1.2
U	6.0	14.25	4.3	3.7
	3.2	14.69	2.4	1.8

The inactivation cross sections of haploid wild-type yeast cells strain 211a were calculated as 1-hit detector based on the track theory in an extended target mode and the new calculation of radial dose distribution. The results of the calculations are generally in agreement with the experimental data in high LET including the thin-down region. There is discrepancy between the calculated cross section and the experimental data for Pb ion bombardment in one experimental value which is much larger than the calculated cross section. We have no explanation for this discrepancy.

References

1 Katz R, Scharma S C, Homayoonfar M. The structure of particle tracks. In: Attix FH ed. Topic in radiation dosimetry, supplement 1. New York: Academic, 1972

2 Kiefer J. Adv Space Res, 1994, **14**:(10)331~338

3 Kiefer J. Rase S, Luggen-Hölscher J *et al.* Mutation induction in yeast by x-ray and heavy ions. In: Booz J, Ebert H G, Harfiel H D ed. Proceeding of Seventh Symposium on Microdosimetry, 1981, 915~925,

4 Waligorski M P R, Loh K S, Katz R. Radiat Phys Chem, 1987, **30**:201~8

5 Butts J J, Katz R. Radiat Res, 1967, **30**:71~855

6 Katz R, Dunn D E, Sinclair G L. Radiat Prot Dosim, 1985, **13**:4~281

7 Zhang C X, Liu X W, Li M F*et al.* Radiat Prot Dosim, 1994, **52**:6~93

8 Zhang C X, Dunn D E, Katz R. Radiat Prot Dosim, 1985, **13**:8~8

9 Kiefer J, Straaten H. Phys Med Biol, 1986, **31**:9~1201

10 Krämer M, Kraft G. Heavy ion track structure calculations, In: Chadwick K H, Moschini G, Varma M N ed. Biophysical modelling of radiation effcts. Adam Higer, 1992